Unmasking neutron star interiors using cooling simulations

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Abstract

We introduce a new tool for "unmasking" the composition of neutron star (NS) interiors which is based on the fact that the state of matter at high densities determines the statistics of both NS observables, the temperature-age (TA) data as well as the mass distribution. We use modern cooling simulations to extract distributions of NS masses required to reproduce those of the yet sparse data in the TA plane. By comparing the results with a mass distribution for young, nearby NSs from population synthesis we can sharpen two NS cooling problems. The *direct Urca (DU) problem* consists in a narrowing of the NS population at the mass value for which the DU process as the most effective cooling mechanism in the hadronic layer of the star can occur. The *Vela mass problem* is a broadening of the population beyond the range of the typical mass window of 1.1 - 1.5 $M_\odot$. Applying this tool to modern EoS we discuss examples for pure hadronic stars which are in conflict with these constraints while hybrid stars with a color superconducting quark matter core can predict a satisfactory mass distribution, provided the smallest diquark pairing gap has a properly defined density dependence.

1 Introduction

The quest for understanding the state of nuclear matter at high densities beyond saturation at $n \gtrsim 0.16$ fm^{-3} has triggered a multitude of theoretical and experimental investigations. It is of principal interest to clarify the mechanism how the quark and gluon substructure of nucleons might manifest itself under extreme compression [1]. One of the central questions is that of deconfinement: nature might choose to excite more massive degrees of freedom of the hadron spectrum such as hyperons and nucleon resonances in order to satisfy the Pauli principle before the quark-gluon plasma shall emerge as expected from the asymptotic freedom property of QCD at ultimate densities. Due to the presence of strong attractive correlations in this intermediate density regime, the transition of hadrons from well-localized quark bound states to delocalized, unbound states is expected to pass a transitory phase of strongly correlated few-quark complexes with frequent resonant scattering processes [2, 3]. Thereby a very rich structure of quark condensates can occur characterizing color superconducting phases in the low-temperature QCD phase diagram, most relevant for compact star physics [1, 4, 5].

Besides terrestrial experiments with relativistic heavy-ion collisions the interior of neutron stars provides a "laboratory" where matter under conditions of extreme densities occurs [6]. The problem is to identify the composition of neutron star interiors from their observable properties like, e.g., masses, radii, rotational and cooling evolution [7, 8].

Until recently the compactness of objects has been discussed as a characteristic feature of stars with a quark matter interior (strange stars) when radii are less than ~ 10 km [9, 10]. The situation has dramatically changed with the advent of precision measurements of high masses for objects like the pulsar PSR J0751+1807 [11] with $M = 2.1 \pm 0.2\ M_\odot$ or of the mass-radius relation from the thermal emission of the isolated neutron star RX J1856-3754 pointing to either large radii of $R > 14$ km for a typical NS mass of $\lesssim 1.4\ M_\odot$ or large masses $M \gtrsim 2.0\ M_\odot$ for radii not exceeding 12 km [12]. These measurements clearly demand a stiff equation of state and exclude standard models for hyperonic or quark matter interiors as well as mesonic condensates, see [13].

As has been argued in [14], there are several modern QCD-motivated quark matter EsoS which could provide enough stiffness of high-density matter to be not in conflict with the new mass and mass-radius constraints. This leads, however, to the effect that hybrid stars with quark matter interiors "masquerade" as neutron stars [15] since they cannot be distinguished from each other by their mechanical properties, see also the contribution by T. Klähn in this volume [16] for a color superconducting three-flavor quark model with selfconsistently determined quark masses and pairing gaps [5, 17].

Therefore, also suggested signals from the timing behavior of pulsar spin-down [18], frequency clustering [19] or population clustering [20, 21] of accreting NSs should not be applicable.

In the present work, we suggest a sensitive tool for "unmasking" the composition of neutron stars which is based on their cooling behavior. As the cooling regulators such as neutrino emissivities, heat conductivity and specific heat in quark matter might be qualitatively different from those in nuclear matter, due to the chiral transition and color superconductivity with some possibly sensible density dependence, the TA curves for hybrid stars could be significantly different from those of neutron stars. In order to reach the goal of unmasking the neutron star interior we introduce here a new method for the quantitative analysis of the cooling behavior consisting in the extraction of a NS mass distribution from the (yet sparse) TA data and its comparison with the (most likely) mass distribution from population synthesis models of NS evolution in the galaxy [22].

2 Cooling curves in the TA diagram

The cooling behavior of compact stars belongs to the most complex phenomena in astrophysics. Therefore, the codes for its numerical simulation as developed by a few groups contain inputs (cooling regulators) of rather different kind, see, e.g., [23, 24, 25, 26, 27]. Attempts to develop a *Minimal Cooling Paradigm* [24] by omitting important medium effects on cooling regulators [26, 28] unfortunately result in inconsistencies and suffer therefore from the danger of being not reliable. To develop a paradigmatic cooling code as an open standard, however, is rather necessary to cross-check the present knowledge of the groups before more sophisticated mechanisms like anisotropies due to the magnetic field [23] or special processes in the NS crust or at the surface are taken into account. Therefore, it is still premature to attempt an identification of the NS interior from the cooling behavior.

In order to circumvent such a model dependence we employ a given cooling code developed in Refs. [25, 29] and vary the matter properties such as EoS, superconductivity and star crust model such as to fulfill all constraints known up to now (mass, mass-radius, TA, brightness, etc.). Moreover, we try to use consistent inputs.

We consider the cooling evolution of young neutron stars with ages $t \sim 10^3 - 10^6$ yr which is governed by the emission of neutrinos from the interior for $t \lesssim 10^5$ yr and thermal photon emission for $t \gtrsim 10^5$ yr.

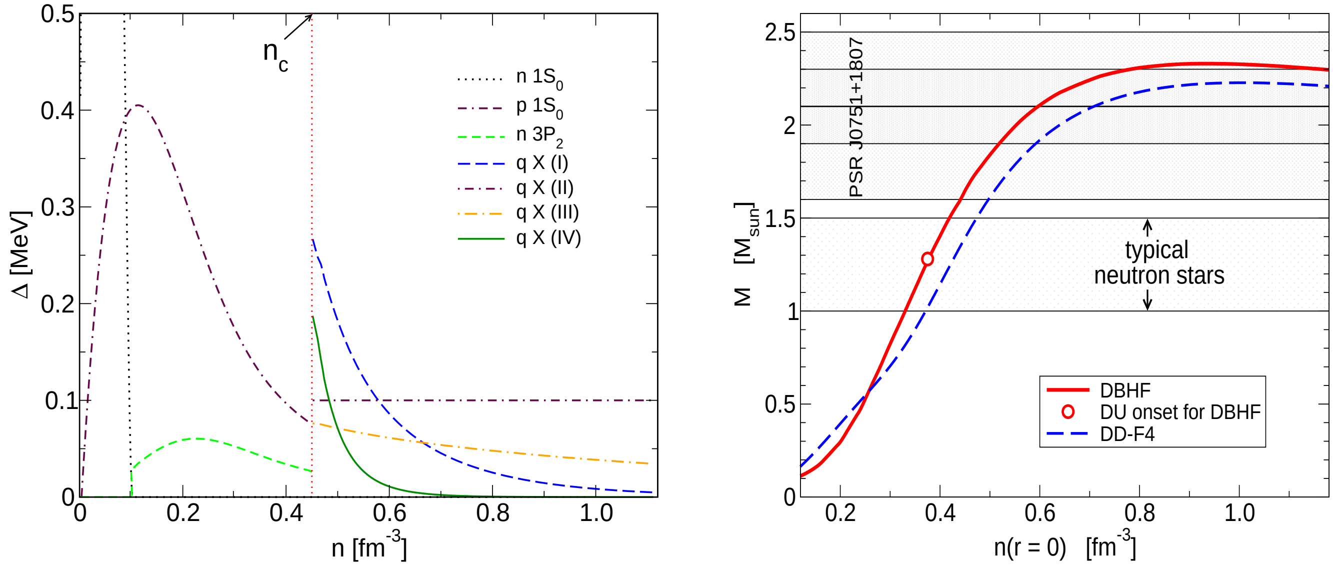


Figure 1: Density dependence of the pairing gaps in nuclear matter together with that of the hypothetical X-gap in quark matter (left). Mass-central density relation for the two hadronic EoS models DBHF and DD-F4 (right). The dot indicates the onset of the DU process.

The internal temperature is of the order of $T \sim 1$ keV. This is much smaller than the neutrino opacity temperature $T_{\rm opac} \sim 1$ MeV as well as critical temperatures for superconductivity in nuclear ($T_c \sim 1$ MeV) or quark matter ($T_c \sim 1-100$ MeV). Therefore, the neutrinos are not trapped and the matter is in a superconducting state. In Fig. 1 we show the density dependence of the pairing gaps in nuclear matter [30, 25] together with that of the hypothetical X-gap in quark matter [31, 32, 33]. The phase transition occurs at the critical density $n_c = 2.75\ n_0 = 0.44$ fm^{-3}.

The main neutrino cooling processes in hadronic matter are the direct Urca (DU), the medium modified Urca (MMU) and the pair breaking and formation (PBF) whereas in quark matter the main processes are the quark direct Urca (QDU), quark modified Urca (QMU), quark bremsstrahlung (QB) and quark pair formation and breaking (QPFB) [34]. Also the electron bremsstrahlung (EB), and the massive gluon-photon decay (see [35]) are included.

The $1S_0$ neutron and proton gaps in the hadronic shell are taken according to the calculations by [30] corresponding to the thick lines in Fig. 5 of Ref. [25]. However, the $3P_2$ gap is suppressed by a factor 10 compared to the BCS model calculation of [30], consistent with arguments from a renormalization group treatment of nuclear pairing [36]. Without such a suppression of the $3P_2$ gap the hadronic cooling scenario would not fulfill the TA constraint, see [28].

The possibilities of pion condensation and of other so called exotic processes are included in the calculations for purely hadronic stars but do not occur in the hybrid ones since the critical density for pion condensation exceeds that for deconfinement in our case [25]. While the hadronic DU process occurs in the DBHF model EoS for all neutron stars with masses above 1.27 $M_\odot$, it is not present at all in the DD-F4 model, see the right panel of Fig. 1. We account for the specific heat and the heat conductivity of all existing particle species contributing with fractions determined by the $\beta-$ equilibrium conditions. Additionally, in quark matter the massless and massive gluon-photon modes also contribute.

In the 2SC phase only the contributions of quarks forming Cooper pairs (say red and green) are suppressed via huge diquark gaps, while those of the remaining unpaired blue color lead to a so fast cooling that the hybrid cooling scenario becomes unfavorable [32]. Therefore, we assume the existence of a weak pairing channel such that in the dispersion relation of hitherto unpaired blue quarks a small residual gap can appear. We call this gap Δ_X and show that for a successful description of the cooling scenario Δ_X has to have a density dependence. We have studied the ansatz

$$\Delta_{\rm X} = \Delta_0 \, \exp\left[-\alpha \left(\frac{\mu - \mu_c}{\mu_c}\right)\right] , \tag{1}$$

where μ is the quark chemical potential, $\mu_c = 330$ MeV. For the analyses of possible models we vary the values of α and Δ_0, given in the Table 1 of [33] and shown in the left panel of Fig. 1.

The physical origin of the X-gap is not yet identified. It could occur, e.g., due to quantum fluctuations of color neutral quark sextet complexes [3]. Such calculations have not yet been performed within the relativistic chiral quark models. The size of the small pairing gaps in possible residual single color/ single flavor channels [37] is typically in the interval 10 keV - 1 MeV, see discussion in [38]. The specific example of the CSL phase is analyzed in more in detail in Refs. [39, 40, 41].

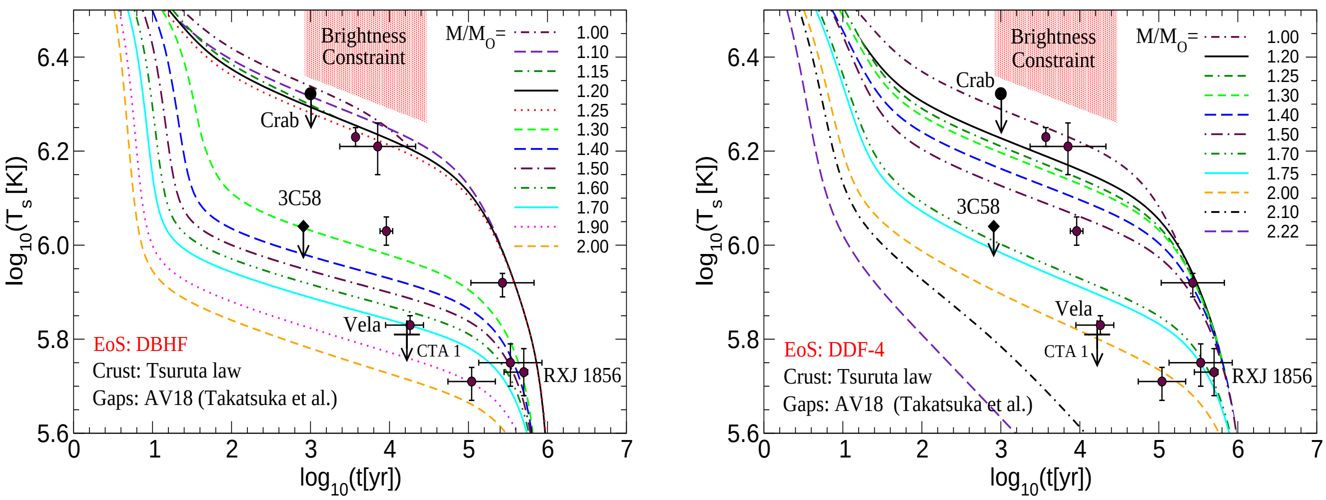
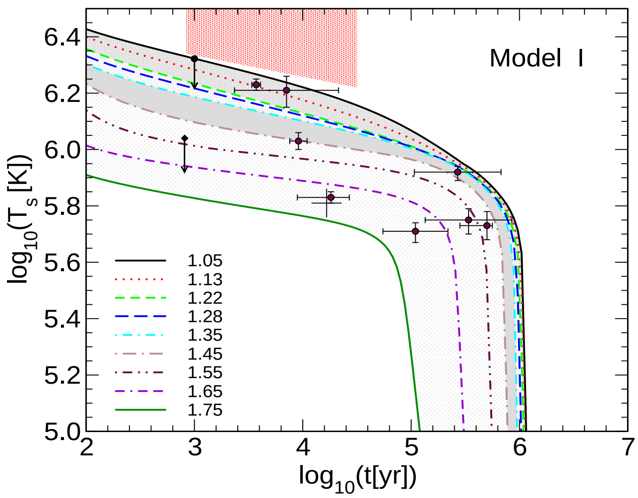


Figure 2: Hadronic star cooling curves for DBHF model EoS. Different lines correspond to compact star mass values indicated in the legend (in units of $M_\odot$), data points with error bars are taken from Ref. [24].

In Fig. 2 we present TA-diagrams for two hadronic star EsoS, where DBHF is an ab-initio calculation for the Bonn-A nucleon-nucleon potential within the Dirac-Brueckner-Hartree-Fock approach [42], discussed in the context of compact star constraints in [43, 44]. DD-F4 denotes a relativistic mean-field model of the EoS with density-dependent masses and coupling constants adjusted to mimick the behavior of the DBHF approach [45, 46]. In the hadronic cooling calculations presented in Fig. 2 the crust model has been chosen according to Tsuruta's formula for the $T_m - T_s$ relationship between be temperatures of the inner crust and the surface [25].

In Fig. 3 we show the TA diagrams for two hybrid star cooling models presented in Ref. [33]. The TA data points are taken from [24]. The hatched trapeze-like region represents the brightness constraint (BC) [47]. For each model nine cooling curves are shown for configurations with mass values corresponding to the binning of the population synthesis calculations explained in [33].

For the hybrid cooling scenario in [33] a more detailed measure for the ability of a cooling model to describe observational data in the temperature-age diagram had been introduced. Also the logN-LogS distribution constraint has been considered. In the TA diagram to encode the likelihood that stars in that mass interval can be found in the solar neighborhood, in accordence with the population synthesis scenario, see Fig. 3 we use a marking with five grey values. The darkest grey value, for example, corresponds to the most populated mass interval 1.35 - 1.45 $M_\odot$ predicted by the mass spectrum used in population synthesis.



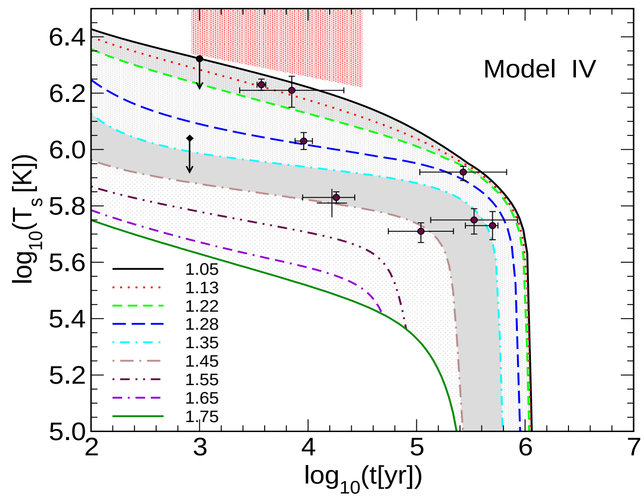


Figure 3: Cooling curves for hybrid star configurations with 2SC+X pairing pattern and X-gap model I (left) versus model IV (right). For the gaps see the left panel of Fig. 1. The grey value for the shading of the mass bin areas corresponds to the probability for that mass bin value in the population synthesis model of Ref. [22].

3 Mass distribution from TA data

In the present work we suggest a method to construct a NS mass distribution as a tool for the quantitative characterisation of a given cooling model using the yet sparsely distributed measurements of cooling neutron stars in the TA plane as a probability measure. This method is described as follows. Once the cooling model is defined by the EoS and the cooling regulators, the configuration corresponding to a gravitational mass M and its cooling curve $T(t;M)$ can be determined. Next a set of mass values M_i, $i = 0, \ldots, N_M$ is introduced, defining the borders of N_M mass bins as, for example, in the population synthesis. A pair of neighboring cooling curves $T(t;M_i)$ and $T(t;M_{i-1})$ corresponds to the i^{th} mass bin and delimits a strip in the TA plane. We now construct a measure for the number of cooling objects to be expected within this mass bin

$$N_i = \sum_{j=1}^{N_{\rm cool}} \int dt \int_{T(t;M_i)}^{T(t;M_{i-1})} dT\, P_j(T,t), \tag{2}$$

where $N_{\rm cool}$ denotes the total number of observed coolers used for the analysis and $P_j(T,t)$ is the probability density to find the j^{th} object at the point (T,t) in the TA plane. For the present exploratory study we make the simplest ansatz that $P_j(T,t)$ is constant in the rectangular region defined by the upper and lower limits of the confidence intervals corresponding to the temperature and age measurements, (T_{jl}, T_{ju}) and (t_{jl}, t_{ju}), respectively,

$$P_j(T,t) = [(t_{jl} - t_{ju})(T_{jl} - T_{ju})]^{-1}\Theta(T - T_{jl})\Theta(T_{ju} - T)\Theta(t - t_{jl})\Theta(t_{ju} - t)\ . \tag{3}$$

Note that in the case when the exact age the object is known (e.g., for a historical supernova), the time-dependence of $P_j(T,t)$ degenerates to a δ-function and the t-integral in (2) can be immediately carried out, leaving us with a one-dimensional probability measure.

This method has been applied to the cooling models for hadronic and hybrid stars described in the previous section. The results for the extracted mass distributions are normalized to 100 objects, defining $N(M) = 100\ N_i/(\sum_{i=0}^{N_M} N_i)$, and shown in Fig. 4.

As we see from Fig. 4, the results are very sensitive to the chosen cooling model. In the hadronic scenario the onset of the DU cooling mechanism drastically narrows the mass distribution around the critical mass for the DU onset, see Fig. 1. On the other hand the slow cooling model predicts more massive objects than could be justified from the independent population analysis.

When comparing the density dependence of the pairing gaps, given in the left panel of Fig. 1, with the extracted mass distributions for the corresponding hybrid models in the right panel of Fig. 4, the direct relationship between the superconductivity and the mass distribution becomes obvious.

The DU problem as it was previously discussed in the literature [25, 43, 48] was based on the intuitive understanding that the mass distribution can not be peaked at a critical mass value which accidentally is unique for all observed young objects. Our modification of the definition of the DU problem does not contradict that suggestion, but rather provides an additional measure which rehabilitates the validity of cooling scenarios including the DU process.

On the other hand, the EoS model should obey the mass constraints too. Therefore, using the models discussed in this work we demonstrate that the most preferable structure of the compact object is likely to be a hybrid star with properly defined color superconductivity of the quark matter state in the core.

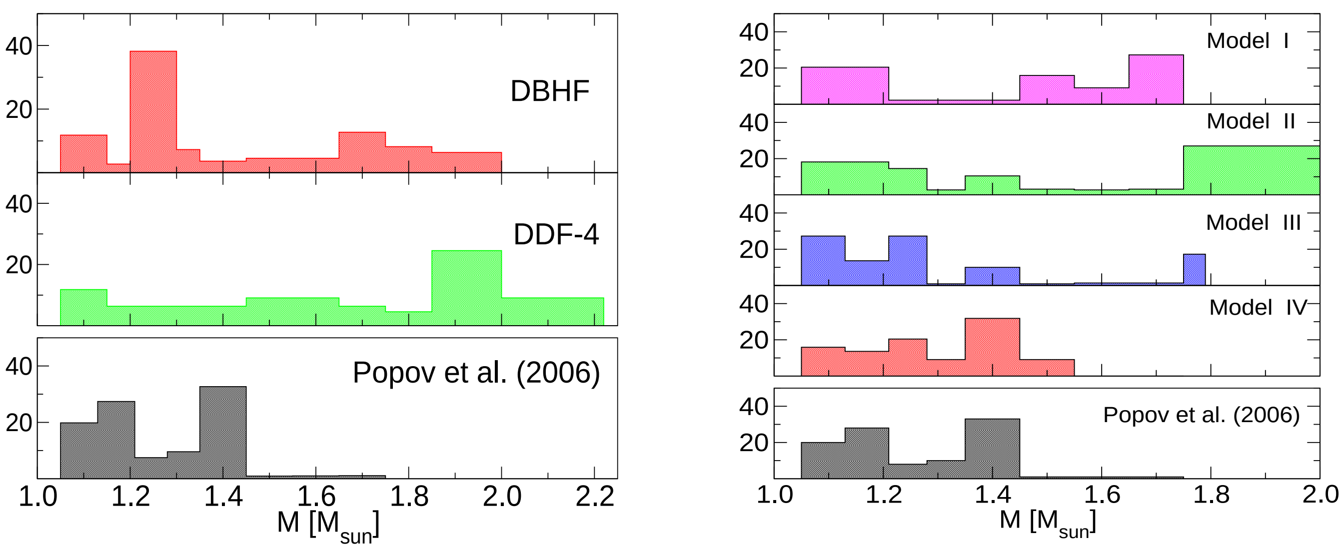


Figure 4: NS mass spectra extracted from the distribution of cooling data for both hadronic EoS models (left panel) and for hybrid stars with X-gap models I-IV (right panel). For comparison, the mass disctribution of young, nearby NS from the population synthesis of Popov et al. [33] is shown at the bottom of the panels.

4 Conclusion

In this contribution we have presented mass distributions obtained by analysing cooling calculations for NSs and demonstrated that they provide a sensible measure for the composition of compact star matter, even if the mechanical properties of the compact objects are almost identical. The comparison with a mass distribution from a population synthesis approach allows to favor hybrid stars with properly defined color superconducting quark matter core over other hybrid star or pure neutron star models. The presented approach makes testable predictions and will be quantitatively improved when a better statistics for TA data will emerge from present and future observational programmes. On the other hand, an improvement of the population synthesis might be required in connection with the ongoing development of supernova modeling and a deeper understanding of astrophysical processes in the galactic neighborhood [49]. The new method presented here to extract a NS mass distribution from the cooling behavior has proven useful as a new tool to unmask the NS interior since it is sensitive to subtle changes in the cooling regulators. It shall therefore be further developed and not be missed out when Astronomy meets QCD [50] and more stringent tests are applied to the behavior of nuclear matter under conditions of extreme densities in neutron stars, a place where the nature of the deconfinement transition can be studied.

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References

[1] D. Blaschke and D. Sedrakian (Eds.), *Superdense QCD Matter And Compact Stars* Springer, Nato Science Series (2006) II/197

[2] G. Röpke, D. Blaschke and H. Schulz, *Phys. Rev.* D 34 (1986) 3499

[3] B. C. Barrois, *Nucl. Phys.* B 129 (1977) 390 .

[4] M. Buballa, *Phys. Rep.* 407 (2005) 205

[5] D. Blaschke, S. Fredriksson, H. Grigorian, A. M. Öztas and F. Sandin, *Phys. Rev.* D 72 (2005) 065020

[6] F. Weber, *Pulsars as astrophysical laboratories for nuclear and particle physics*, Bristol, UK: IOP (1999)

[7] M. Prakash, I. Bombaci, M. Prakash, P. J. Ellis, J. M. Lattimer and R. Knorren, *Phys. Rep.* 280 (1997) 1

[8] D. Blaschke, N. K. Glendenning and A. Sedrakian, (Eds.): *Physics of neutron star interiors*, Springer, Lecture Notes in Physics, Vol. 578 (2001)

[9] I. Bombaci, *Lect. Notes Phys.* 578 (2001) 253

[10] X. D. Li, I. Bombaci, M. Dey, J. Dey and E. P. J. van den Heuvel, *Phys. Rev. Lett.* 83 (1999) 3776

[11] D.J. Nice, et al., *Astrophys. J.* 634 (2005) 1242

[12] J. E. Trümper, V. Burwitz, F. Haberl and V. E. Zavlin, *Nucl. Phys. Proc. Suppl.* 132 (2004) 560

[13] F. Özel, Nature **441** (2006) 1115.

[14] M. Alford, et al., *arXiv:* astro-ph/0606524 (2006)

[15] M. Alford, M. Braby, M. W. Paris and S. Reddy, *Astrophys. J.* 629 (2005) 969

[16] T. Klähn, *arXiv:* nucl-th/0611078 (2006)

[17] T. Klähn, D. Blaschke, F. Sandin, C. Fuchs, A. Faessler, H. Grigorian and G. Röpke, *arXiv:* nucl-th/0609067 (2006)

[18] N. K. Glendenning, S. Pei and F. Weber, *Phys. Rev. Lett.* 79 (1997) 1603

[19] N. K. Glendenning and F. Weber, *Astrophys. J.* 559 (2001) L119

[20] G. S. Poghosyan, H. Grigorian and D. Blaschke, *Astrophys. J.* 551 (2001) L73

[21] D. Blaschke, I. Bombaci, H. Grigorian and G. S. Poghosyan, *New Astron.* 7 (2002) 107

[22] S. Popov, H. Grigorian, R. Turolla and D. Blaschke, *Astron. & Astrophys.* 448 (2006) 327

[23] D. Page, U. Geppert and F. Weber, *Nucl. Phys.* A 777 (2006) 497

[24] D. Page, J. M. Lattimer, M. Prakash and A. W. Steiner, *Astrophys. J. Suppl.* 155 (2004) 623

[25] D. Blaschke, H. Grigorian and D. N. Voskresensky, *Astron. & Astrophys.* 424 (2004) 979

[26] D. N. Voskresensky, *Lect. Notes Phys.* 578 (2001) 467

[27] D. G. Yakovlev, A. D. Kaminker, O. Y. Gnedin and P. Haensel, *Phys. Rep.* 354 (2001) 1

[28] H. Grigorian and D. N. Voskresensky, *Astron. & Astrophys.* 444 (2005) 913

[29] D. Blaschke, H. Grigorian and D. N. Voskresensky, *Astron. & Astrophys.* 368 (2001) 561

[30] T. Takatsuka and R. Tamagaki, *Prog. Theor. Phys.* 112 (2004) 37

[31] D. Blaschke, D. N. Voskresensky and H. Grigorian, *Compact Stars. The Quest for New States of Dense Matter* World Scientific, Singapore (2004) 409

[32] H. Grigorian, D. Blaschke and D. Voskresensky, *Phys. Rev.* C 71 (2005) 045801

[33] S. Popov, H. Grigorian and D. Blaschke, *Phys. Rev.* C 74 (2006) 025803

[34] P. Jaikumar and M. Prakash, *Phys. Lett.* B 516 (2001) 345

[35] D. Blaschke, T. Klähn and D. N. Voskresensky, *Astrophys. J.* 533 (2000) 406

[36] A. Schwenk and B. Friman, *Phys. Rev. Lett.* 92 (2004) 082501

[37] T. Schäfer, *Phys. Rev.* D 62 (2000) 094007

[38] M. G. Alford, J. A. Bowers, J. M. Cheyne and G. A. Cowan, *Phys. Rev.* D 67 (2003) 054018

[39] D. N. Aguilera, D. Blaschke, M. Buballa and V. L. Yudichev, *Phys. Rev.* D **72** (2005) 034008

[40] A. Schmitt, I. A. Shovkovy and Q. Wang, *Phys. Rev.* D 73 (2006) 034012

[41] D. N. Aguilera, D. Blaschke, H. Grigorian and N. N. Scoccola, *Phys. Rev.* D **74** (2006) in press

[42] E.N.E. van Dalen, C. Fuchs, and A. Faessler, *Phys. Rev. Lett.* 95 (2005) 022302

[43] T. Klähn et al., *Phys. Rev.* C 74 (2006) 035802

[44] H. Grigorian, D. Blaschke and T. Klähn, *arXiv:* astro-ph/0611595 (2006)

[45] S. Typel, *Phys. Rev.* C 71 (2005) 064301

[46] S. Typel, T. Klähn, F. Sandin, D. Blaschke, *in preparation* (2006)

[47] H. Grigorian, *Phys. Rev.* C 74 (2006) 025801

[48] E. E. Kolomeitsev and D. N. Voskresensky, *Nucl. Phys.* A 759 (2005) 373

[49] S. B. Popov, D. Blaschke, H. Grigorian and M. E. Prokhorov, *arXiv:* astro-ph/0606308 (2006)

[50] S. B. Popov, D. Blaschke, H. Grigorian and B. Posselt, *arXiv:* astro-ph/0609524 (2006)